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A study of recoating in stereolithography

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Abstract: Recoating in a stereolithography apparatus (SLA) involves dipping the part being built into a vat containing liquid resin and sweeping a blade over the top of the part. There are two problems with the recoating operation in existing SLA systems. Firstly, the process is slow because the blade sweep speed is usually restricted to minimize disturbances to the resin surface and also because, after each sweep, the machine has to wait idly for any disturbances to subside and the resin surface to become level before scanning by the laser can be performed. In a part made up of hundreds or thousands of layers, these measures considerably lengthen the build time. The second problem is the difficulty of ensuring that the thickness of the generated layers is even and accurate in parts that incorporate upward-facing concave areas. For such parts, recoated layers may be either thinner or thicker than specified. In the worst case, the part may become delaminated or the blade may strike the cured resin during recoating, resulting in build failure. This paper reports on an experimental study of the recoating operation. The paper discusses the setting of parameters controlling the operation and proposes guidelines for producing good quality SLA parts while reducing build times.

Keywords: rapid prototyping, stereolithography, recoating, trapped volume

NOTATION

a	layer thickness
D	distance from the base of the trapped volume to the edge of the blade
g	blade gap
h_i	height at i
H	resin height from the base of the trapped volume to the top of the recoated layer
l	dimension of the trapped volume along the sweep direction
Q_i	volumetric flow at section i–i
Q_o	volumetric flow at section o–o
$v(z)$	velocity profile in the z direction
V	blade sweep speed
y	sweep direction
z	build direction

1 INTRODUCTION

The stereolithography apparatus (SLA) rapid prototyping process employs a laser to polymerize and solidify a photosensitive viscous liquid resin layer by layer. An SLA has a platform which carries the part being constructed and a vat containing the resin material. The platform is lowered gradually into the vat as the part is built up. To start a new layer during the part building phase, a coat of fresh resin is thinly spread on top of the immediately preceding cured section. This recoating operation [**1**] consumes time because of the need for a delay to allow a freshly drawn or hatched layer to cure before dipping the part further into the resin, in addition to sweeping with a blade over the top of the part and waiting for the ripples on the disturbed resin surface to subside and the surface to become level. The latter step, called a z-level wait [**2**], takes place before drawing and hatching by the laser can start. In order to reduce disturbances to the resin surface, the blade sweep and the platform dipping speeds are usually kept low. These measures add to the recoating time which, although only in the order of seconds, is a significant part (as much as 90 per cent) of the total build time. Also, because the laser is not turned off while the machine is recoating between layers, the useful life of the laser, which is the most expensive consumable in the machine, is shortened. The second problem is with the quality of the resin layers obtained. To achieve the required layer thickness and uniformity, the recoating operation must be controlled precisely, since any errors at this stage will be directly reflected in the next layer [**1**]. However, this is not always possible. The most difficult situation is recoating over a feature that isolates a volume of resin from the surrounding liquid polymer.

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The level of the resin in the trapped volume may be different from that outside. As a consequence, the recoated resin on top of the part would be subject to the meniscus effect and become uneven. Thus, the part accuracy deteriorates and eventually the build could fail because of collisions of the blade with the part. Also, where there is too much resin, delamination could occur due to undercuring.

Originally, the SLA recoating process involved dipping the part into the resin to ensure that the top of the part is fully covered with resin. However, this requires a very long z-level wait time for the excess resin on top of the part to drain away. Subsequently, a blade was introduced, which improved the process by sweeping off the excess resin after the deep-dip operation to leave a coat of fresh material for the next layer. An improved blade design was introduced in 1996 by one of the main manufacturers of SLAs for their new range of machines [**3**]. The new blade is an 'active' blade, which holds resin within it and deposits a controlled amount on the part. This has eliminated the need for the deep-dip operation and enabled the production of parts of a more consistent quality. However, the above-mentioned problems remain, and recoating over trapped volumes is still difficult.

Research to improve the recoating process is continuously being undertaken [**4–10**]. Resin film recoating methods have been proposed [**4**, **5**]. Systems using vibration methods [**6**], counter-rotating rollers, ink-jet recoaters and spinning devices [**7**] have also been patented. A new concept of recoating for parts with inserts has been described [**8**]. However, the majority of SLA machines currently available commercially employ blades for the recoating operation. Renap and Kruth [**9**] have described the recoating problems associated with the original passive blade. This paper addresses issues with the speed and quality of SLA recoating using an active blade.

The body of the paper comprises two sections. The first discusses the setting of the parameters controlling the recoating operation to raise the blade sweep speed and decrease the z-level wait, while also limiting the amount of rippling. The second section focuses on other sets of recoating parameters to achieve a good recoating quality, especially for trapped volumes, and provides guidelines for selecting parameters to achieve high-quality parts in reduced build times.

2 INCREASING THE SPEED OF RECOATING

To ensure trouble-free recoating and good-quality parts, it is essential that the surface of the liquid resin is level and any ripples caused by previous movements of the blade and platform have settled before the laser starts scanning the next layer. This section discusses the determination of the minimum z-level waiting time required to achieve a smooth and level resin surface and analyses the relationship between the recoating time and the speeds of movement of the blade and the platform. An SLA-250 machine [**2**], equipped with an active blade for recoating, was used in this investigation. The resin type was Cibatool® SL 5170 [**2**].

2.1 Control parameters

For the purpose of recoating, the SLA process can be divided into two stages. These are initial support construction and part building. Supports connect the part with the platform and reduce the risk of delamination and deformation. The machine starts with building supports on the platform to a predetermined height. As the supports are thin, there is no blade sweeping during the recoating operation which, at this stage, only involves the platform dipping into the resin and then rising to the building position. There are three parameters relating to the platform movements. These are dip distance, velocity and acceleration. The dip distance was not considered in this study because its value is normally decided by the required coating quality. Thus, only platform velocity and acceleration were investigated.

Because part building is the main stage in the SLA process, the recoating time during this stage is more significant. As previously mentioned, during part building the blade sweeps over the part, spreading new resin for the next layer (Fig. 1). The platform moves down by one layer thickness before the blade starts to sweep. As the movement of the platform is very small, it does not affect the recoating time greatly. The parameters of interest are the blade sweep speed and the vacuum level in the blade, with the latter affecting the rate at which the resin spreads over the part.

2.2 Tests

A phototransistor was used to pick up fluctuations in the level of the resin [**11**]. The device was placed at the centre and along the side walls of the vat. From the signals detected, it was found that ripples took longer to subside at points along the side walls. Therefore, measuring points were selected along the side walls at front, middle and back positions (see Fig. 2).

The directions of movement of the blade are defined as inward and outward (see Fig. 2). The sweep time is the time for the blade to complete one sweep. Although it might be expected that higher sweep speeds would cause larger ripples needing longer settling times, tests showed that the settling time did not change much, even

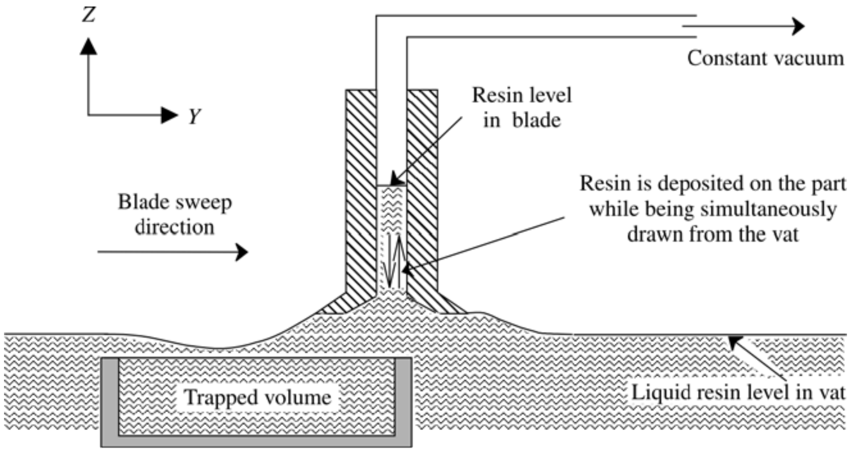


Fig. 1 Active recoating blade

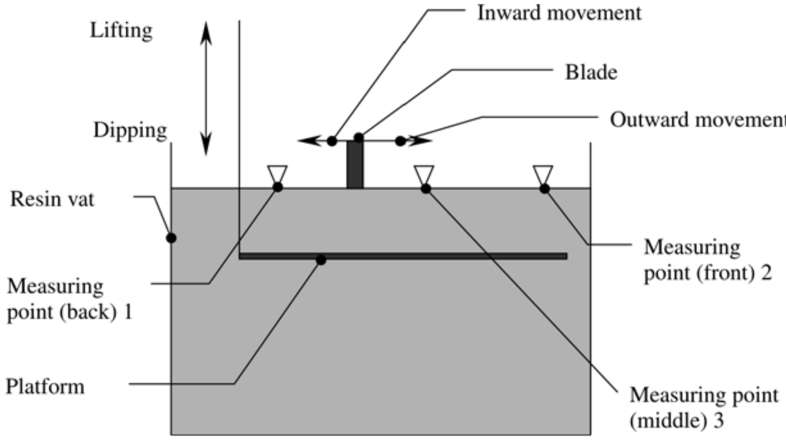


Fig. 2 Test set-up

when the sweep speed was increased significantly. This led to the possibility of reducing the total recoating time by increasing the sweep speed. Therefore, the investigation was biased towards high sweep speeds (or shorter sweep times). Tests were carried out at four different nominal sweep times, ranging from 10 to 4 s. Three vacuum levels were employed, with level 1 corresponding to low vacuum and level 3 to high vacuum. Different combinations of measuring points, blade motion directions, sweep times and vacuum levels were used, which resulted in 72 measurements being taken.

Following the same idea, tests relating to the movements of the platform also concentrated on faster speeds. As the platform is driven by a leadscrew, the leadscrew speed and acceleration were varied. Three different values of leadscrew speed and four different accelerations were adopted, namely 1.26, 1.89 and 2.51 rad/s and 1.26, 1.89, 2.51 and 3.14 rad/s^2 respectively. Thus, 36 measurements were taken with different combinations of measuring points, speeds and accelerations.

2.3 Results

2.3.1 *Calibration and data processing*

Calibration was carried out to determine how the amplitude of the phototransistor signal varies with the level of the resin. As shown in Fig. 3, an approximately linear relationship between the output of the phototransistor and the resin level was found within the range of level changes of interest (± 0.1 mm).

The processing of the data obtained using the phototransistor will be illustrated with reference to Fig. 4. A tolerance band is first chosen to define when the ripples have become small enough to be ignored. In Fig. 4, the band is ± 0.005 mm or equal to 5 per cent of the thickness of the resin layers. The reference surface level is determined by averaging the last 300 measurements. As shown in the figure, the surface level falls into, and remains within, the tolerance band 13.74 s after measurements started. As the blade began moving at 3.14 s, the recoating time needed to achieve settlement within the

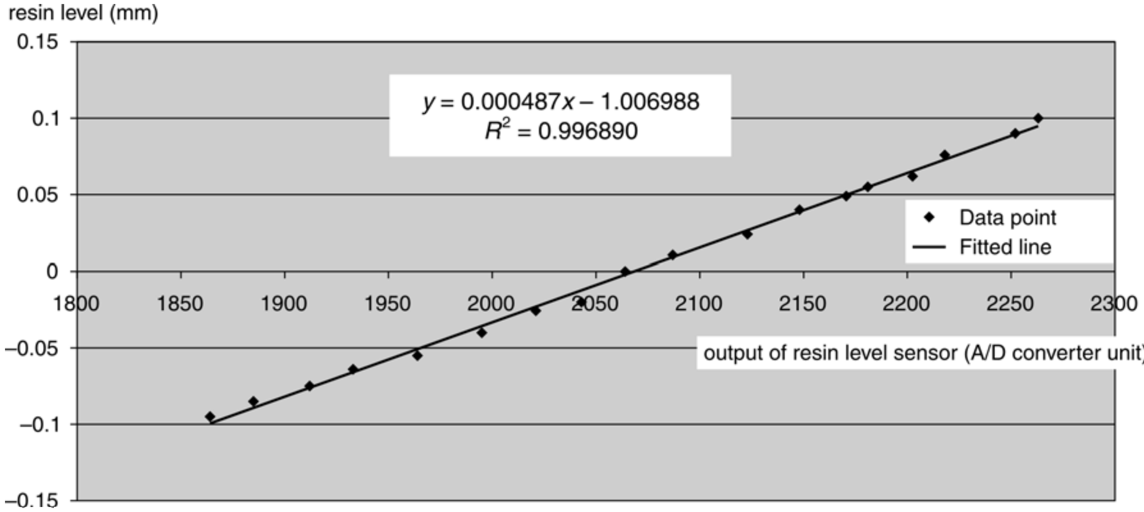


Fig. 3 Relationship between the resin level and phototransistor response

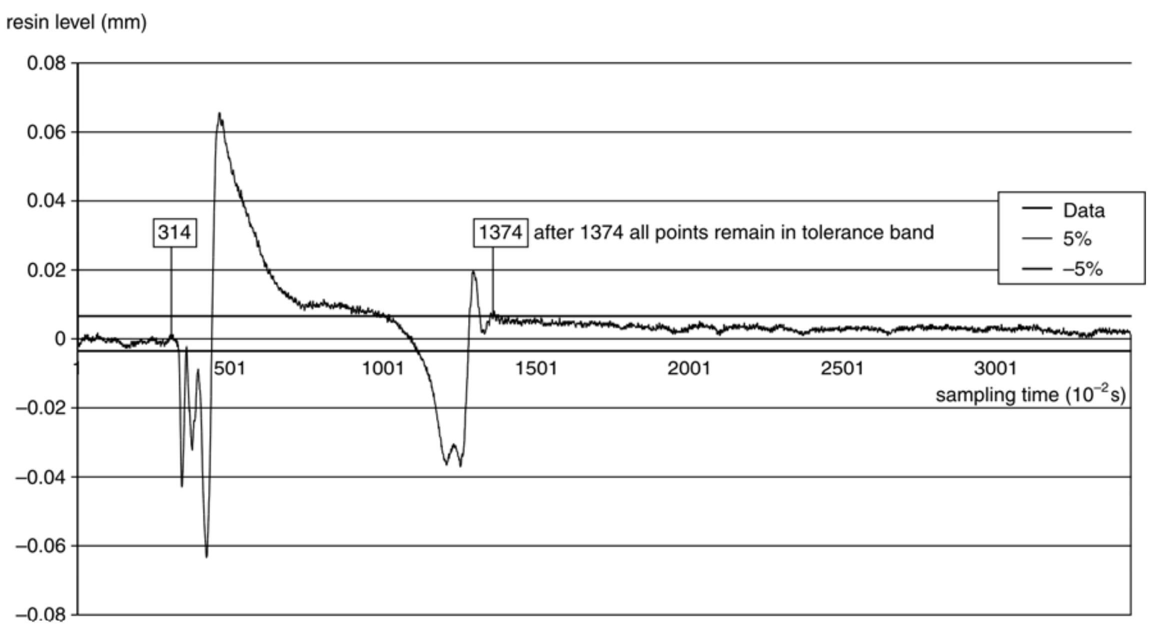


Fig. 4 A plot of the data obtained using the phototransistor

5 per cent tolerance band is $RT_{5\%} = 13.74 - 3.14 = 10.6$ s. This includes the blade sweep time and the ripple settling time. From Fig. 4, the blade can be seen to take much longer to sweep than the ripples to settle.

2.3.2 *Blade movements*

The data obtained were plotted for each measurement. This reveals that large ripples travel with the blade. The magnitudes of the ripples can be higher than 0.5 mm during the blade sweep tests, with the largest ripples appearing at the back of the vat (see Table 1). Also, the resin surface oscillates around the blade when it stops in the vat. Based on these observations, it can be deduced that rippling takes longer to subside with inward movements of the blade than with outward movements. This can generally be noticed in the data of Table 2, which shows the sum of the blade sweep time and the ripple settling time. In most cases, the times for inward movement are larger than for outward movement, with those for inward movement recorded at the back measuring points being the largest of all.

Due to the difference in settling times between the inward and outward sweeping of the blade, different z-level waiting times might be prescribed for the machine. Also, because the ripples behind the blade settle faster than those in front, the waiting time of the laser could be

Table 1 Ripple amplitudes (in mm) at different measuring points

Measuring point	Ripple amplitude (mm) Front		Middle		Back		
Motion direction	Inward	Outward	Inward	Outward	Inward	Outward	Nominal sweep time (s)
Vacuum 3	0.065	0.068	0.171	0.114	0.543	0.576	10
	0.075	0.071	0.169	0.098	0.493	0.521	8
	0.101	0.096	0.185	0.113	0.421	0.424	6
	0.118	0.155	0.230	0.160	0.342	0.359	4
Vacuum 2	0.067	0.063	0.157	0.106	0.534	0.561	10
	0.076	0.072	0.162	0.094	0.483	0.492	8
	0.102	0.097	0.182	0.114	0.412	0.419	6
	0.121	0.155	0.228	0.165	0.332	0.350	4
Vacuum 1	0.069	0.064	0.158	0.095	0.481	0.573	10
	0.079	0.070	0.157	0.096	0.487	0.503	8
	0.100	0.098	0.178	0.119	0.417	0.423	6
	0.117	0.159	0.227	0.170	0.333	0.356	4

reduced by starting the scanning of the new layer on the aft side of the blade.

Table 2 also shows that when the blade sweep time is reduced, the recoating time also drops without being noticeably affected by the greater disturbances to the resin surface associated with the increased blade speed. This is because the blade sweep time is the major part of the total recoating time and the settling time for the ripples does not increase much with the sweep speed, as noted earlier. Therefore, as previously mentioned, a higher sweep speed should be adopted wherever possible. Finally, from Table 2, it can be seen that the effect of the vacuum level is small although vacuum setting 3 generally gave better results than the other settings.

2.3.3 *Platform movements (during support recoating)*

The results presented in Table 3 show no marked differences in timing between the different operating conditions. It would appear that, as the speed and acceleration were increased to reduce the travel time of the platform, the ripples would take longer to subside, with the net effect that the total time, allowing for the ripples to settle within the given tolerance band, remained approximately constant. There is therefore no effective recommendation regarding platform movements during the support construction stage. However, the lowest acceleration setting seemed to yield the best outcome.

2.4 Guidelines for increasing the speed of recoating

Based on the results obtained, the following guidelines for increasing the speed of recoating can be drawn up:

1. Use high blade sweep speeds, as this does not incur penalties in terms of unduly extending the settling times for the ripples on the resin surface. In any case,

Table 2 Combined blade sweep and ripple settling time (in s) to allow the ripples to settle within a ± 0.01 mm tolerance band

Measuring point	Sum of actual sweep time and settling time (s) Front		Middle		Back		
Motion direction	Inward	Outward	Inward	Outward	Inward	Outward	Nominal sweep time (s)
Vacuum 3	9.94	9.54	12.54	9.48	12.79	9.36	10
	8.04	7.6	8.13	7.74	10.39	7.6	8
	6.19	6.27	6.32	7.29	8.61	6.01	6
	4.43	5.41	4.55	4.79	6.97	4.61	4
Vacuum 2	9.8	9.3	12.65	9.61	14.04	9.52	10
	9.08	7.8	9.52	7.87	15.68	7.57	8
	6.17	6.26	6.58	5.96	9.38	6.32	6
	4.42	4.58	5.28	5.09	7.78	4.52	4
Vacuum 1	9.87	9.46	16.2	9.52	13.53	9.4	10
	8.15	7.6	8.34	8.39	13.25	7.67	8
	6.18	6.3	10.12	5.98	8.12	6.07	6
	4.43	4.44	5.95	4.25	7.57	4.59	4

Table 3 Combined platform movement and ripple settling time (in s) to allow the ripples to settle within a ± 0.01 mm tolerance band

	Sum of platform movement and ripples settling times (s)			
Acceleration (rad/s^2)	Front	Middle	Back	Speed (rad/s)
1.26	13.79	13.7	13.49	1.26
	13.44	13.67	15.15	1.89
	13.1	13.87	13.6	2.51
1.89	14.93	16.05	14.02	1.26
	13.32	14.21	13.53	1.89
	12.19	14.42	14.02	2.51
2.51	13.25	16.37	14.08	1.26
	13.24	12.95	14.44	1.89
	12.28	15.22	14.03	2.51
3.14	14.98	14.94	14.63	1.26
	12.48	14.09	13.66	1.89
	11.38	14.77	13.21	2.51

it takes much longer for the blade to complete a sweep than for the ripples to settle down.

2. Adopt different pause lengths for the cases of the blade sweeping inward and outward as the settling times are different.
3. Begin the scanning of a new layer on the aft side of the blade as the ripples subside faster behind the blade.
4. Adopt low platform accelerations.

3 IMPROVING THE QUALITY OF RECOATING

The last section has shown that a significant reduction in recoating time can be achieved while maintaining a smooth and level resin surface when a higher sweep speed is used. However, in addition to the resin surface having to be smooth and level, part quality also depends on the accuracy of the thickness of the applied coat of resin and other factors such as the magnitude of the drag forces exerted on the part by the moving blade and the amount of leading edge material deposit [**12**]. A higher sweep speed could adversely affect these factors and result in poor quality. Experiments were carried out to determine situations where high sweep speeds can be adopted. The main factors examined were the thickness and evenness of the resin layers, as they also take into account the amount of leading edge material deposit and the drag forces would have had to be sufficiently small for the part to be built successfully. Recoating experiments were conducted on both solid substrates (without concave areas) and parts with trapped volumes. The equipment used was an SLA-3500 equipped with an active blade [**3**]. The resin was of type SL5510 [**13**].

3.1 Recoating over a solid substrate

Figure 5 shows the test part, a common SLA benchmark component. Note that the square and round holes at the four corners of the part are all through holes and the part does not contain any trapped volumes. Four parts were built, one using default values for the blade sweep speed and z-level waiting time, the second with a sweep speed three times the default value, the third with a

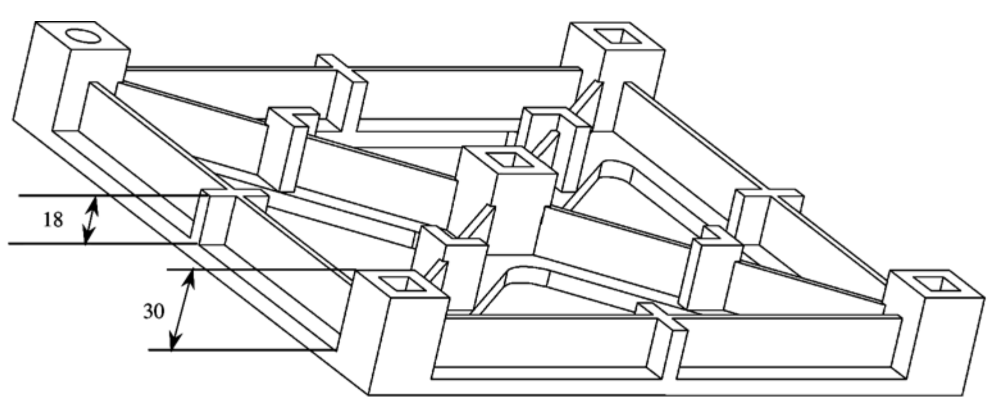


Fig. 5 Benchmark part

Table 4 Measured thickness values (in mm) for benchmark part

Recoating condition	Thickness (mm)	
Default sweep speed and waiting time	18.02	30.01
Three times default sweep speed	18.02	30.03
One-third of default waiting time	18.01	30.01
Three times default sweep speed and one-third of default waiting time	18.01	29.99
Nominal thickness	18.00	30.00

z-level waiting time equal to one-third of the default value and the fourth using both the increased sweep speed and shortened z-level wait. All the parts were built with a layer thickness of 0.1 mm and the blade gap set equal to 200 per cent of the layer thickness. Table 4 shows the thickness measurements taken at two fixed points (see Fig. 5) on each test part. It can be seen that the higher sweep speed and reduced z-level wait did not affect the accuracy in the z direction of the parts. This means that the specified layer thickness is maintained precisely. Therefore, the thickness of the recoated layer is constant and independent of the blade sweep speed within the test range. As a result, higher sweep speeds and shorter z-level waits can be adopted when recoating solid substrates.

It will now be shown that, for the thickness of the recoated layer to be constant and independent of the sweep speed, the profile of the velocity of the resin beneath the blade should be triangular. Consider Fig. 6, which depicts a blade travelling at a speed V from left to right over the substrate. The resin can be regarded as flowing from right to left (from section i–i to section o–o in Fig. 6). Relative to the edge of the blade, the speed of the resin layer in contact with it is zero, while the resin at the top of the substrate moves at the speed V of the blade. At section i–i, the resin flow speed $v(z)$ changes from V to 0. The volumetric flow Q_i is given by

$$Q_i = \int_0^g v(z)\, dz$$

where g is the blade gap (the distance from the top of the

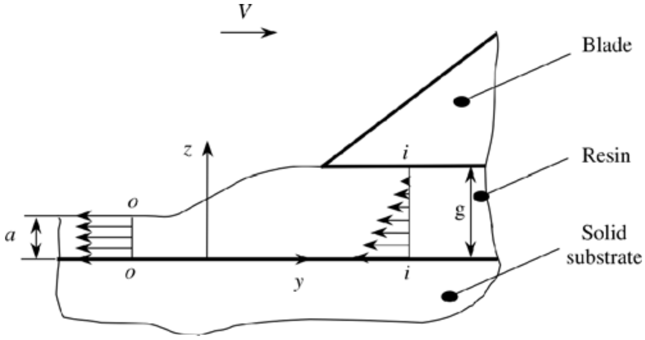


Fig. 6 Flow under the blade and resin velocity profile

part to the edge of the blade). The profile of $v(z)$ (or the resin velocity profile, RVP) depends on the blade speed, the blade gap and the viscosity of the resin. At section o–o, the resin flow speed is uniform, so the volumetric flow Q_o is given by

$$Q_o = aV$$

where a is the thickness of the deposited coat of resin. As no other flow exists, Q_i should be equal to Q_o. Hence,

$$a = \frac{\int_0^g v(z)\, dz}{V}$$

For the recoated layer thickness a to remain constant ($0.5\,g$), $v(z)$ should vary linearly with z as follows:

$$v(z) = V\left(1 - \frac{z}{g}\right)$$

where $z = 0$ at the top of the substrate, i.e. the profile of $v(z)$ should be close to a triangle, as stated above.

3.2 Recoating over trapped volumes

The amount of resin inside a trapped volume depends on the recoating parameters. As a result, the level of the trapped resin may be different from that of the surrounding resin if incorrect recoating parameters are used. The blade can scoop out too much material or it can leave an excessive amount behind.

It can be seen in Fig. 1, that liquid resin is maintained in a reservoir within the blade by a vacuum pump. When the laser has finished solidifying a layer, the part is lowered to create a user-specified clearance from the blade. The blade then moves along the top surface of the part, applying a thin, even coating of resin. The blade reservoir is replenished during, and immediately following, the recoating process by drawing liquid resin up from the resin surface in the surrounding vat.

When the blade passes over a trapped volume, the liquid flow beneath the blade is complex. A triangular velocity profile is no longer obtained because of the large gap between the blade and the solid substrate. Although the flow is difficult to model, it is clear that the amount of resin left in the trapped volume is influenced by the sweep speed, the distance from the top of the part (bottom of the trapped volume) to the edge of the blade, the geometry of the trapped volume and the viscosity of the resin.

If the amount of trapped resin is too little, the level of the resin within the trapped volume will be lower than that in the vat. This condition is called starvation [3]. When too much resin is left in the trapped volume, mounding occurs [3]. This is the case where the resin level inside the trapped volume is above that in the vat. Starvation can result in the cured part showing a slight downward slope towards the trapped volume.

Mounding gives an increased cured resin height along the borders of the trapped volume, potentially leading to collision of the blade against the part or delamination of the layer being built.

3.2.1 Starvation and mounding tests

A test part was designed to investigate the phenomena of starvation and mounding. The part consisted of a series of square hollow bosses of different heights. The axes of the bosses were vertical and the hollows faced upwards in the vat so that they trapped resin during the build. The horizontal $(x\text{–}y)$ cross-sections of the bosses were all $20\,\text{mm} \times 20\,\text{mm}$ in internal dimensions and 2 mm in thickness. The nominal heights of the different bosses were between 0.1 and 14.4 mm. After the part was built, the height of each boss was measured using a microscope at four different locations (see Fig. 7a). The four measurements, h_1 to h_4, were used to determine the occurrence of starvation and mounding and detect the possibility of blade collision, as explained below.

Firstly, a parameter defined as the edge offset was computed:

$$\text{Edge offset} \triangleq \frac{(h_2 - h_1) + (h_3 - h_4)}{2}$$

If the edge offset was negative, a starvation condition was indicated. If the edge offset was positive, mounding was deemed to have taken place.

Secondly, the height error was calculated:

$$\text{Height error} \triangleq \max(h_1, h_2, h_3, h_4) - \text{specified nominal height}$$

If the height error was positive, there was a risk of the blade colliding against the part.

With the machine recoating parameters (the gap between the blade and substrate, sweep speed, number of sweeps per layer and z-level wait) set for normal operation, the test part was built. The height measurements were taken and the results plotted in Fig. 7b. It can be seen that both the edge offset and the height error start with a negative value and then change back to positive as the part height increases. This means that starvation and mounding had occurred. As some height errors are quite large, there have been many opportunities for blade collision. It can also be noted that starvation happened in the shorter bosses with shallow trapped volumes. As the boss height increased and the trapped volume became deeper, mounding replaced starvation and the danger of blade collision increased. Blade collision actually occurred at a height of 8.7 mm.

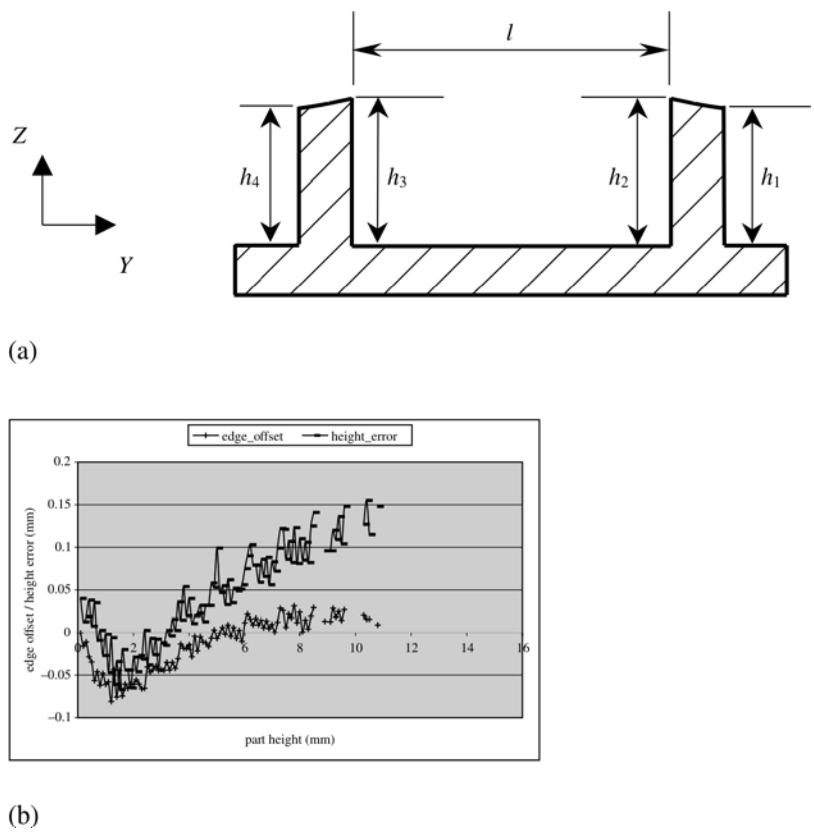


Fig. 7 (a) Measured dimensions; (b) edge offsets and height errors for normal operating conditions

Clearly, the build parameters for normal operation were not appropriate for parts containing trapped volumes.

3.2.2 *Effects of operating conditions*

The same part was built with different recoating parameters as follows:

Part 1. Initially, when the bosses were shallow, a low sweep speed was adopted to increase the amount of resin left in the trapped volumes. As the heights of the bosses increased, a higher sweep speed was set to reduce mounding. The other machine parameters were as for normal operation.

Part 2. This part was built using three sweeps of the recoating blade per layer. The other machine parameters were as for normal operation.

Part 3. For this part, the *z*-level wait (before starting scanning and after sweeping) was longer (45 s) compared to the normal pause (15 s).

Part 4. A blade gap 2.5 times the layer thickness was adopted for this part.

The results obtained are plotted in Figs 8a and b.

These figures show that applying different sweep speeds (low speeds for shallow trapped volumes and high speeds for deep volumes) gave the best recoating results with the least edge offsets and height errors. Adopting a large blade gap also helped to reduce edge offsets, although there was a greater degree of mounding. Applying three sweeps of the recoating blade per layer had a similar effect to the longer *z*-level wait. However, for part 3, for which the extended *z*-level wait strategy was employed, the build failed when the height was 9.7 mm. As there is only one layer of resin at the top connecting the trapped volume and the free surrounding liquid, increasing the *z*-level wait would not help much in levelling the isolated and the free resin.

3.2.3 *Effects of part geometry*

The resin velocity profile between the blade and the part depends on the height or depth (*z* dimension) of the trapped volume. This influences the quality of the recoating represented by the edge offset and height error, as evidenced by the experimental results obtained.

It can be seen that the resin velocity profile and recoating quality might also be affected by the size and shape (*xy* geometry) of the cross-section of the trapped volume and its orientation relative to the direction of the blade sweep (the *y* direction). Test parts were designed to investigate the effects of the dimensions and geometry of the trapped volume in the *xy* plane and also those of the thickness of the wall enclosing the trapped resin, as follows:

Parts 5, 6, 7 and 8. These parts were bosses with internal dimensions of 10 mm × 10 mm, 30 mm × 30 mm, 30 mm × 20 mm and 20 mm × 30 mm. The wall thickness of the bosses was 2 mm in all cases.

Part 9. This part was a boss of internal dimensions 20 mm × 20 mm with a thicker wall (4 mm) than in the other parts.

The parts were built using the recoating parameters for normal operation. The results are shown in Figs 9a and b. A phenomenon also evident in Fig. 8 was observed, namely that starvation occurred at the lower portions of a trapped volume and then gave way to mounding as the trapped volume increased in height. Among those parts with the same wall thickness of 2 mm, the edge offsets and height errors were larger for part 5, which had the smallest cross-section. Also, mounding first occurred at a height of 2 mm, much earlier than for the other parts. The offsets and errors in part 6 were smaller and mounding started later at 8 mm. The situation for part 8 was similar to that for part 6. Both parts had the same dimensions in the direction of the blade sweep. The recoated quality of part 7 was worse than that of part 8, although both had the same cross-sectional area. It should be noted that the longer dimension in the case of part 8 was aligned with the sweep direction, whereas in the case of part 7 the longer dimension was perpendicular to the sweep direction. The edge offsets for part 9, which had a thicker wall, were larger than for the other parts, but its height errors were smaller.

In summary, the quality of the recoating, as manifested in the final accuracy achieved, was better for the larger trapped volumes. The dimension in the blade sweep direction had a greater influence on quality than that in a direction perpendicular to the sweep. Smaller edge offsets were obtained for trapped volume enclosures with thinner walls.

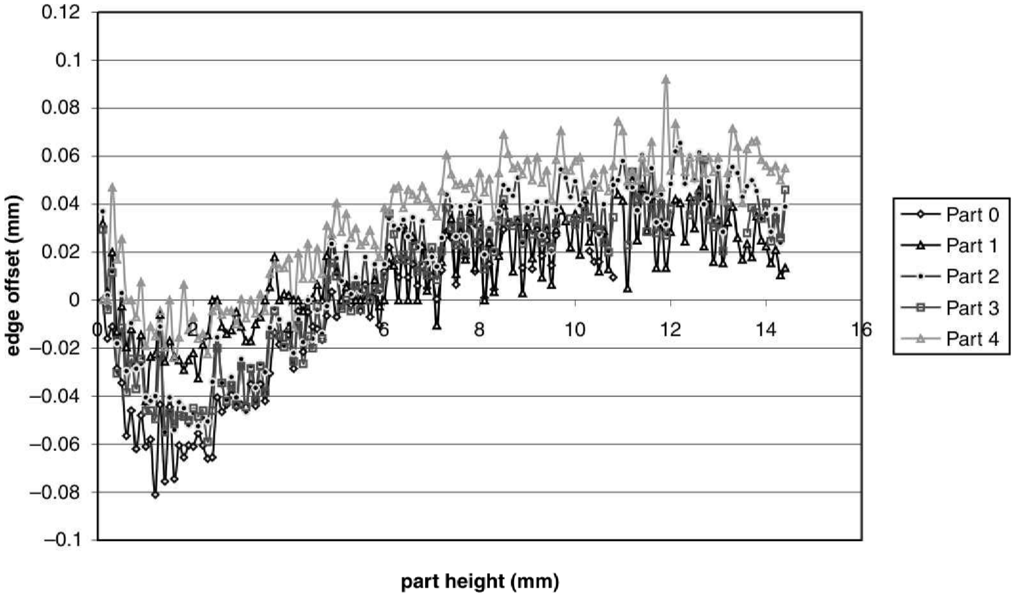
3.2.4 *Discussion*

A common phenomenon in recoating over trapped volumes is that starvation occurs initially, followed by mounding. This is because the RVP varies with the depth of the trapped volume. When the latter is shallow, the RVP is still close to a triangle (Fig. 10a). The volumetric flow Q_i at section *i–i* is therefore

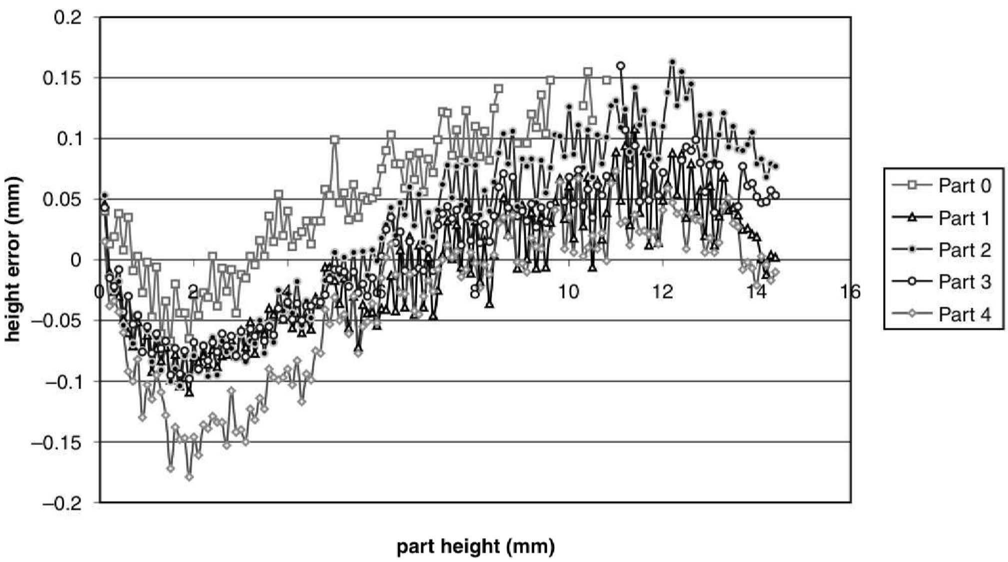
$$Q_i = \int_0^D v(z)\,\mathrm{d}z \cong \tfrac{1}{2}VD$$

where D is the distance from the bottom of the trapped volume to the edge of the blade. At section *o–o*, the volumetric flow Q_o is given by

$$Q_o = HV$$



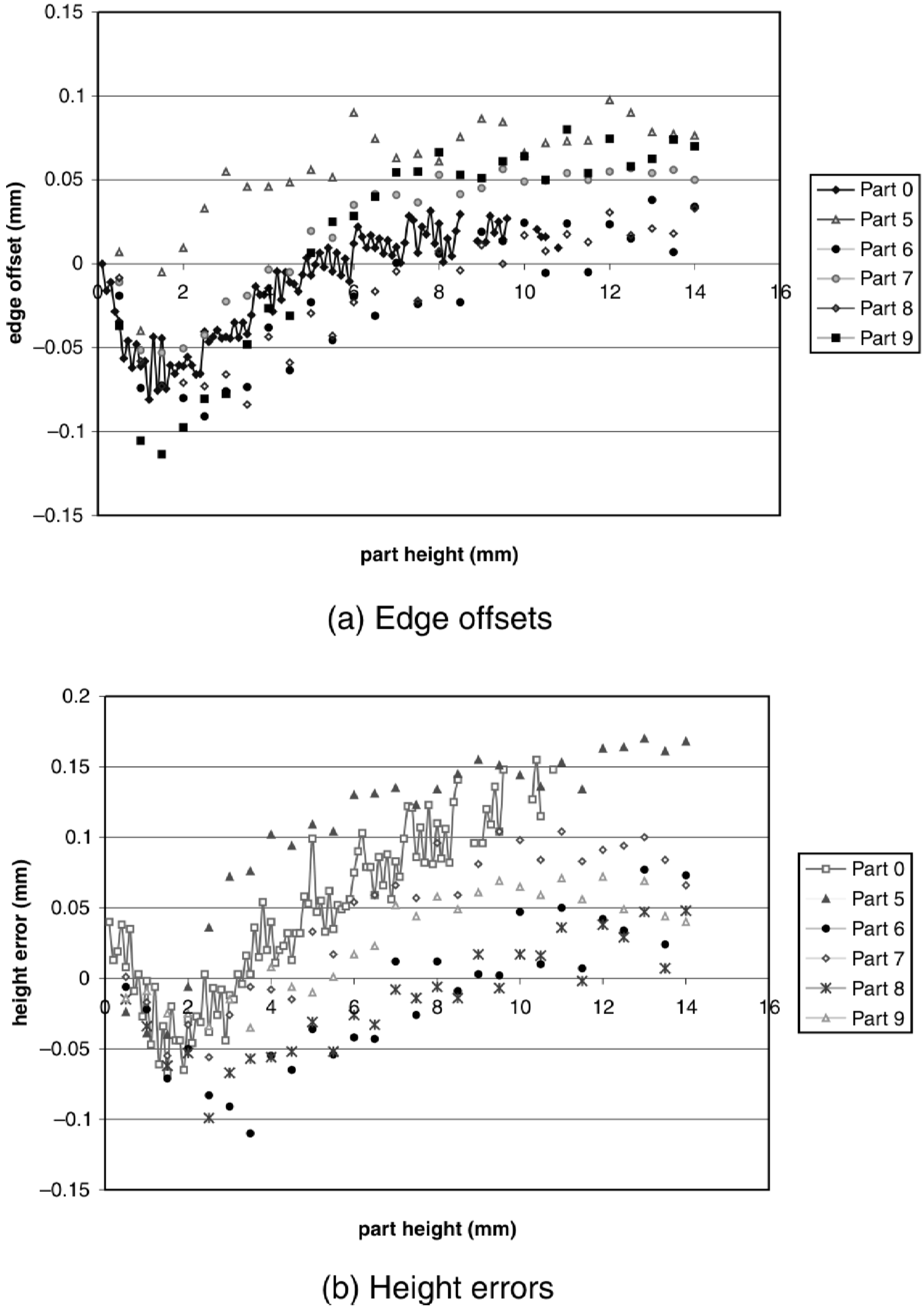
(a) Edge offsets



(b) Height errors

Fig. 8 Edge offsets and height errors for parts produced under different conditions

where H is the height of the resin from the bottom of the trapped volume to the top of the newly recoated layer. Equating Q_i and Q_o gives $H \cong 0.5D$. For the first layer, choosing D, the blade gap, to be equal to twice the thickness a of a layer gives $H = a$, the desired value. During the recoating of the second layer, the new value for D is $D = 2a + a = 3a$ and H is therefore $1.5a$, less than the expected height of $2a$. To compensate for this, the blade sweep speed can be reduced, so that the RVP is changed (Fig. 10b) and $Q_i > \frac{1}{2}VD$. Alternatively, the blade gap can be increased. It has been found that a value of $1.75a$ can be achieved for H by widening the blade gap. As the depth of the trapped volume increases and the RVP becomes similar to the profile shown in Fig. 10c, starvation gives way to mounding. To reduce mounding, a high sweep speed is required.



(a) Edge offsets

(b) Height errors

Fig. 9 Edge offsets and height errors for parts of different geometries

Another observation is that the dimension l (see Fig. 7a) of the trapped volume along the sweep direction has a critical effect on the recoating quality. This can also be explained by the change to the RVP as the blade sweeps across the trapped volume. When the blade edge just passes the entry to a trapped volume or approaches the exit from it, the RVP is different from that in the middle of the trapped volume. This results in the volumetric flows at the entry and exit differing from that in the middle. The flow differences can either cause more resin to build up in the trapped volume or to be removed from it. In either case, the effect on the level in the trapped volume will be greater when l is small than when it is large. This explains why mounding occurred earlier for part 5, which had the smallest value for l (10 mm).

The main factors influencing the process of recoating over trapped volumes have been identified as the blade

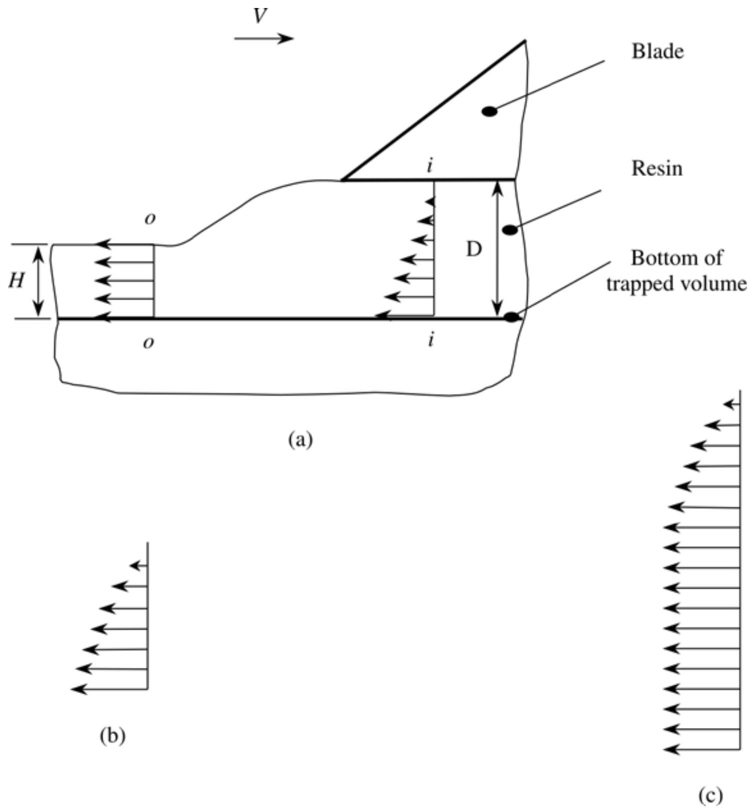


Fig. 10 (a) $v(z)$ over shallow trapped volume; (b) $v(z)$ for reduced sweep speed; (c) $v(z)$ over deep trapped volume

sweep speed and the dimensions and orientation of the trapped volume. Based on the results observed, the following guidelines for successful recoating of parts with trapped volumes can be formulated:

1. At the beginning of a build, a lower sweep speed or a larger blade gap should be applied to help reduce starvation.
2. As the height of the part increases, the sweep speed should be raised to decrease mounding.
3. The longer dimension of the trapped volume should be placed in the *y* direction (the sweep direction) to reduce edge offsets and height errors.

4 CONCLUSIONS

This paper has studied the feasibility of building quality SLA parts at higher speeds than normally recommended by SLA manufacturers. In general, selecting fast recoating parameters is to be encouraged, particularly if there are no trapped volumes. However, caution should be adopted when recoating a shallow trapped volume, where slower recoating parameters are required.

The study has found that using a high blade sweep speed has a number of advantages:

1. Reducing the total time needed for sweeping and *z*-level wait in recoating. The settling time of the ripples does not change much when the blade speed is increased and so the full benefit of decreasing the sweep time is obtained.
2. Helping to minimize mounding over a trapped volume above a certain height.
3. Saving time while maintaining quality when recoating over solid substrates.

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REFERENCES

1 Jacobs, P. F. *Stereolithography and Other RP&M Technologies*, 1996 (ASME Press, New York).

2 *Maestro Workstation User Guide*, p/n 21261-M09-02 Rev. A, 1998 (3D Systems, Valencia, California).
3 *Part Build with the Zephyr Recoating System*, August 1996 (3D Systems, Valencia, California).
4 **Cohen, A. L.** Resin film recoating method and apparatus. US Pat. 5,096,530, 1992.
5 **Gilio, M., Kruth, J.-P.** and **Vanherck, P.** High-speed curtain recoating for stereolithography. *Solid Freeform Fabrication Proc.*, 2001, 46–54.
6 **Jacobs, P. F., Thompson, J. S., Nguyen, H. D.** and **Smalley, D. R.** Vibrationally enhanced stereolithographic recoating. US Pat. 5,693,144, 1997.
7 **Almquist, T. A., Hull, C. W., Thayer, J. S., Leyden, R. N., Jacobs, P. F.** and **Smalley, D. R.** Rapid recoating of three-dimensional objects formed on a cross-sectional basis. US Pat. 5,902,537, 1999.
8 **Geving, B., Kataria, A., Moore, C., Ebert-Uphoff, I., Kurfess, T. R.** and **Rosen, D. W.** Conceptual design of a generalized stereolithography machine, http://www.srl.gatech.edu/research/RTTB/JUSFA00_13172.pdf.
9 **Renap, K.** and **Kruth, J. P.** Recoating issues in stereolithography. *Rapid Prototyping J.*, 1995, **1**(3), 4–16.
10 **Wu, M. L., Zhao, W. H., Li, D. C.** and **Lu, B. H.** Resin recoating thickness in stereolithography. *J. Xi'an Jiaotong Univ.*, 2002, **36**(1), 47–50.
11 **Pham, D. T., Ji, C.** and **Wang, Z.** Setting of re-coating parameters for SLA. In Proceedings of 16th National Conference on *Manufacturing Research*, London, September 2000, pp. 73–80.
12 **Almquist, T. A., Hull, C. W., Modrek, B., Jacobs, P. F., Lewis, C. W., Cohen, A. L., Spence, S. T., Nguyen, H. D., Lewis, M. A., Liran, A.** and **Smalley, D. R.** Recoating stereolithographic layers. US Pat. 6,048,487, 2000.
13 *Vantico, RenShape® SL 5510*, http://www.tooling.vantico.com/tooling/stereoL.rhtm?catID = 8554&parentID = 8512.